GEORGIA DOT RESEARCH PROJECT 18-26

FINAL REPORT

IMPLEMENTATION OF A VARIABLE SPEED LIMIT/RAMP METERING STRATEGY TO INCREASE FREEWAY CAPACITY AT METERED ON-RAMPS

OFFICE OF PERFORMANCE-BASED MANAGEMENT AND RESEARCH

600 WEST PEACHTREE STREET NW
ATLANTA, GA 30308

TECHNICAL REPORT DOCUMENTATION PAGE

<table>
<tr><td>1. Report No.:
FHWA-GA-20-1826</td><td>2. Government Accession No.:
N/A</td><td colspan="2">3. Recipient's Catalog No.:
N/A</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle:
Implementation of a Variable Speed Limit/Ramp Metering strategy to increase freeway capacity at metered on-ramps</td><td colspan="2">5. Report Date:
October 2020</td></tr>
<tr><td colspan="2">6. Performing Organization Code:
N/A</td></tr>
<tr><td colspan="2">7. Author(s):
Jorge A. Laval (PI), Ph.D. (https://orcid.org/0000-0002-0986-4046) and Tu Xu (https://orcid.org/0000-0002-6285-1412)</td><td colspan="2">8. Performing Organization Report No.:
18-26</td></tr>
<tr><td colspan="2" rowspan="2">9. Performing Organization Name and Address:
School of Civil and Environmental Engineering
Georgia Institute of Technology
790 Atlantic Dr.
Atlanta, GA 30332-0355
404-894-2360
jorge.laval@ce.gatech.edu</td><td colspan="2">10. Work Unit No.:
N/A</td></tr>
<tr><td colspan="2">11. Contract or Grant No.:
PI#0013186</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address:
Georgia Department of Transportation
Office of Performance-based
Management and Research
600 West Peachtree St. NW
Atlanta, GA 30308</td><td colspan="2">13. Type of Report and Period Covered:
Final; February 2019 – October 2020</td></tr>
<tr><td colspan="2">14. Sponsoring Agency Code:
N/A</td></tr>
<tr><td colspan="4">15. Supplementary Notes:
Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.</td></tr>
<tr><td colspan="4">16. Abstract:
The objectives of this project are to perform detailed micro-simulation and fine-tuning of the VSL control strategy TORBO at two merge bottlenecks in the I-285 corridor, and to produce all the necessary input for its implementation in MaxView. The optimal settings and the fine-tuning of TORBO were carried out using our microscopic simulation tool GTsim, which specializes in the accurate representation of merging maneuvers in freeway traffic. We found that turbo reduces total travel time is reduced by more than 10 % compared to the status quo.</td></tr>
<tr><td colspan="2">17. Keywords:
Variable Speed Limit, Ramp Metering, Genetic Algorithm Optimization</td><td colspan="2">18. Distribution Statement:
No Restriction</td></tr>
<tr><td>19. Security Classification (of this report):
Unclassified</td><td>20. Security Classification (of this page):
Unclassified</td><td>21. No. of Pages:
27</td><td>22. Price:
Free</td></tr>
</table>

Form DOT 1700.7 (8-72)

Reproduction of completed page authorized.

GDOT Research Project No. 18-26

Final Report

IMPLEMENTATION OF A VARIABLE SPEED LIMIT/RAMP METERING STRATEGY TO INCREASE FREEWAY CAPACITY AT METERED ON-RAMPS

By

Jorge A. Laval, Ph.D.
Professor – School of Civil and Environmental Engineering

Tu Xu
Graduate Research Assistant

Georgia Tech Research Corporation

Contract with
Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation
Federal Highway Administration

October 2020

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Georgia Department of Transportation (GDOT) research project RP14-14 (Laval et al. 2019) proposed TORBO, a combined variable speed limit (VSL) and ramp metering (RM) algorithm designed to maximize freeway capacity by avoiding the capacity drop phenomenon at merge bottlenecks. It was found that the new algorithm is effective in preventing a capacity drop in that the ensuing travel time savings are significant compared to the ramp-metering-only option.

In this project, the research team performed detailed micro-simulation and fine-tuning of the VSL control strategy TORBO at two merge bottlenecks in the I-285 corridor. This objective was accomplished with a simulation-based optimization framework using the GTsim microsimulation application, which allows us to optimize the coordinated operation of VSL control with the existing RM control, and to forecast travel times to improve the efficiency of VSL control. We found that TORBO reduces the total travel time by at least 10% compared to the status quo.

The research team recommends GDOT to revise the current VSL algorithm to incorporate other traffic features (density, flow, and capacity) so that the proposed VSL-RM can contribute improving capacity of the freeway and reducing travel time. Unfortunately, the field implementation was not possible due to technological limitations in the IT infrastructure that cannot be circumvented within the time and funding scope of this project. In particular, the VSL data from NaviGAtor cannot be interfaced in real time with the ramp-metering data from MaxView. Hopefully, these technological setbacks will be removed going forward to allow for efficient congestion management in Georgia freeways.

CHAPTER 1. INTRODUCTION

Georgia's first variable speed limit (VSL) system is operational since October 2014 along the northern half of I-285. This VSL system dynamically changes the speed limits on different sections of the corridor depending on congestion to "harmonize traffic". Research project RP14-14 has demonstrated that GDOT's current speed harmonization system increases travel times by about 5% compared to no control. This is not surprising: existing implementations of VSL throughout the world, which are based on speed harmonization, have shown benefits stemming from incident reductions, but there is no evidence of freeway capacity improvements.

In RP14-14 (Laval et al. 2019), the PI and his team proposed TORBO, a VSL and ramp metering (VSL+RM) strategy designed to increase capacity at metered on-ramp bottlenecks and showed that it can reduce travel times by 8% in the corridor. TORBO was designed to prevent and recover from the so-called "capacity drop phenomenon" at merge bottlenecks. This phenomenon can be responsible for up to 20% losses in freeway capacity due to the merging frictions when congestion sets in. TORBO effectively uses VSLs as mainline meters coordinated with the ramp meters to minimize merging frictions.

The objective of this project is to perform detailed micro-simulation and fine-tuning of the VSL control strategy TORBO at two merge bottlenecks in the I-285 corridor. This objective is accomplished with a simulation-based optimization framework using the GTsim microsimulation application, which allows us to optimize the coordinated operation of VSL control with the existing ramp metering control.

CHAPTER 2. LITERATURE REVIEW

This chapter presents a literature review of the effects of VSL on traffic flow, research methodologies on VSL such as the kinematic wave model, capacity drops, simulation modeling, and traffic control.

VARIABLE SPEED LIMIT

To the best of our knowledge, the earliest VSL systems were proposed by (Smulders 1990), who aimed to homogenize and stabilize traffic to improve flow and safety. Subsequent studies presented the effectiveness of VSL in terms of the enhancement of safety and the reduction of accidents (Abdel-Aty et al. 2006, Abdel-Aty et al. 2008, Lee et al. 2006), the efficiency of traffic flow (Bertini et al. 2006, Papageorgiou et al. 2008), and reductions of shock waves. (Hegyi et al. 2005, Hegyi et al. 2008) Recent studies have suggested that combining VSL and ramp metering or near future technology such as connected vehicles (CV) would reinforce the benefits of the VSL system. (Chen and Ahn 2015, Han et al. 2017, Khondaker and Kattan 2015) Notice that this project does not assume the presence of automated vehicles.

Variable Speed Limit and Ramp Metering

Ramp Metering ALINEA

Ramp metering (RM) has been shown to be effective at increasing mainstream outflow by controlling the inflow of on-ramps. The most popular algorithm of ramp metering is ALINEA, a local feedback strategy that calculates metering rates $r(t)$ using past time-step metering rates $r(t-\Delta t)$ and differences between current and target occupancy $(\hat{o}-o_{out}(t))$, see equation (1), Figure 1. (Papageorgiou et al. 1997)

$$r(t) = r(t-\Delta t) + K_R\big(\hat{o} - o_{out}(t)\big) \tag{1}$$

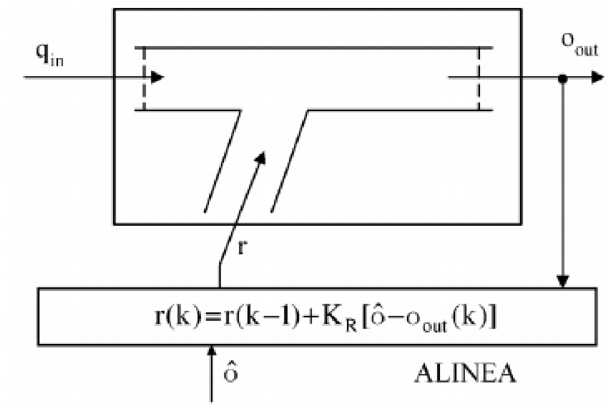

Figure 1. Illustration. ALINEA: local ramp metering strategy (Papageorgiou and Kotsialos 2002)

Queue Flush in Ramp Metering

A restrictive metering rate of an on-ramp induces a queue to spill back to the upstream arterial road. To prevent this situation from occurring, queue flush systems are a common solution (Chilukuri 2015, Chilukuri et al. 2013), which turns off the ramp meter signal when a loop detector installed at the end of the queue storage detects a queue spillback. Chilukuri et al. (2013) found that although a queue flush resolves the queue of the on-ramp, it decreases flow on the mainline freeway, see Figure 3. The queue flush algorithm consists of maximum and minimum density thresholds (k_{max}, k_{min}) of loop detectors and the number of data collecting time periods (n), shown in the following equation.

$$k_{max} \geq \frac{\sum_{i=1}^{n} k_i}{n}$$
$$k_{min} \leq \frac{\sum_{i=1}^{n} k_i}{n}$$

VSL and RM Integrated System

The research group that developed the ALINEA control strategy proposed to use the VSL as a RM. (Carlson et al. 2010b) In their work, VSL decreases the mainstream flow to the potential bottleneck segment, resulting in delaying bottleneck activation at under-critical occupancies (Figure 2). Their assumption of the impact of VSLs on traffic flow is based on empirical data. (Papageorgiou et al. 2008)

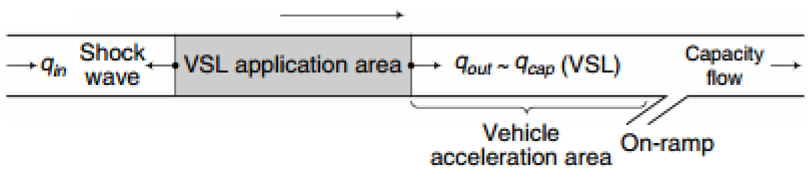

Figure 2. Illustration. Persistent flow control via VSL (Carlson et al., 2010b)

Assuming that the VSL acts as a RM, the research team proposed the integrated optimal control system on the VSL/RM combined network using the METANET traffic flow model and expressed the VSL impact as $v(k) = v^{*}b_m(k)$, where $b_m(k)$ is the magnitude of speed limits ($b_m(k) < 1$). The main objective of the control is to find the minimum total time spent, considering VSL magnitude $b_m(k)$, the ramp queue length, and traffic oscillation costs. After comparing the results of four scenarios—No-Control, Coordinated Ramp Metering, VSL Control, and VSL and RM Integrated Control—they showed that integrated control surpasses other cases and further tested their system on large-scale networks. (Carlson et al. 2010a)

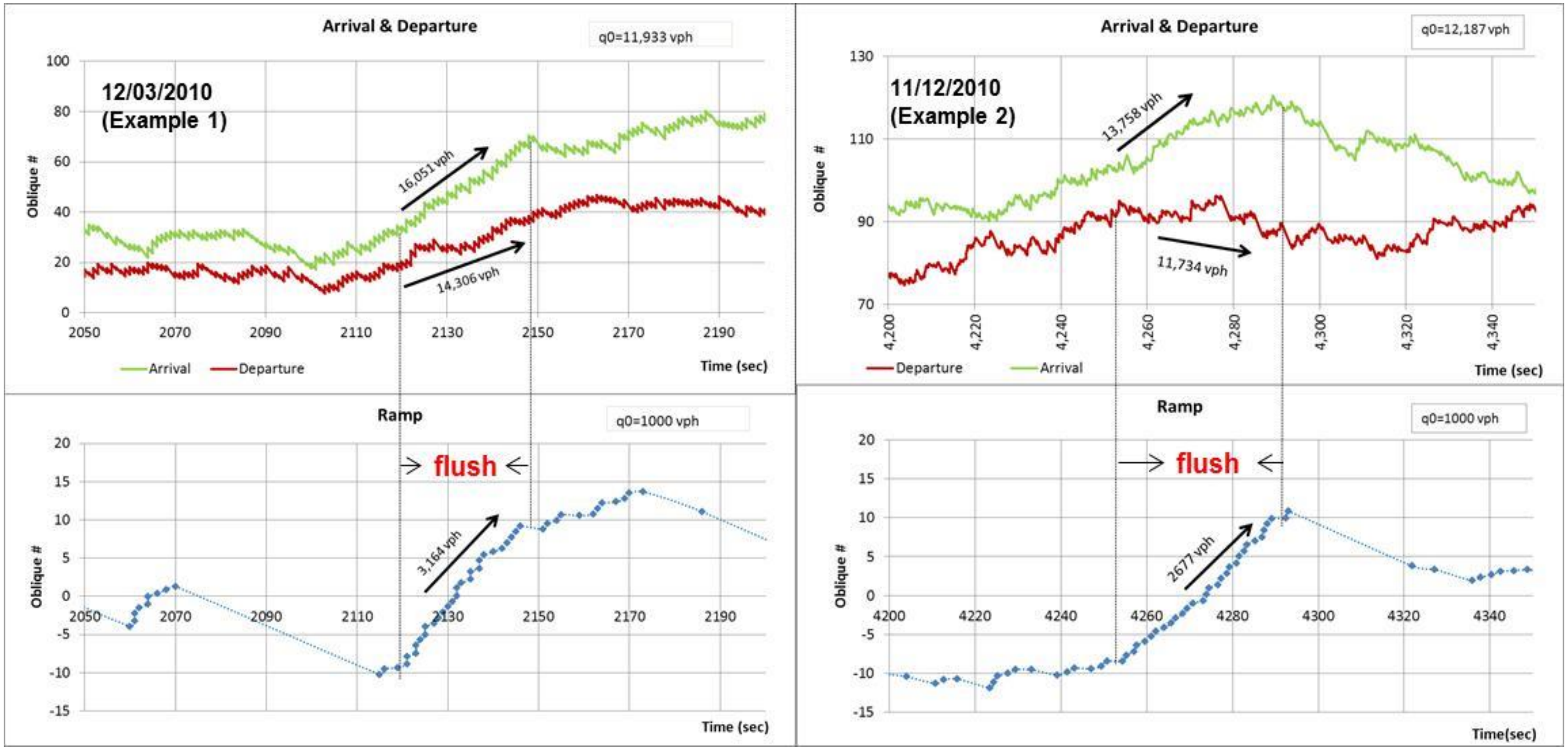

Figure 3. Graph. Two examples for increase in on-ramp flow and decrease in mainline freeway flow during a queue flush (a) 12/03/2010 (left column) (b) 11/12/2010 (right column) (Chilukuri et al. 2013)

Despite the outstanding simulation results from the previous work, the VSL and RM integrated control based on the optimal control method encountered challenges in practical applications because of the limitations and restrictions related to practical traffic systems. To overcome these challenges, Carlson et al. (2011) and Carlson et al. (2014) further proposed a feedback-based VSL and RM control in which traffic flow modeling and systems objectives were the same as those of the previous work, but instead of optimal control, they chose feedback-based control (Figure 4).

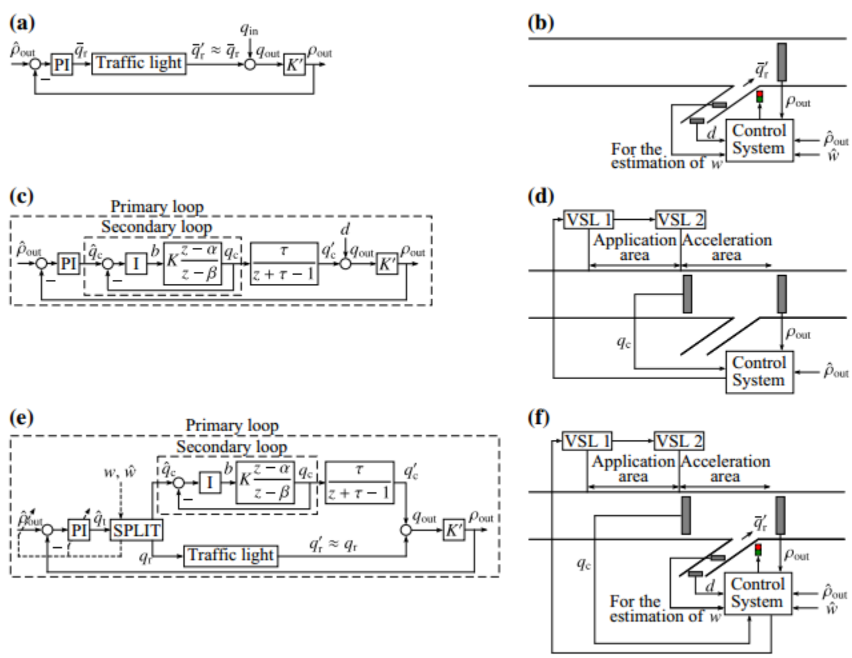

Figure 4. Illustration. (a) PI-ALINEA (feedback RM); (b) RM network; (c) feedback VSL; (d) VSL network; (e) feedback integrated control (RM and VSL); (f) RM and VSL integrated network (Carlson et al. 2014).

Using METANET, the team tested the feedback-based model and compared it to optimal control and several other scenarios. They found that the integrated feedback-based model saves close to the same amount of total travel time as the optimal control model. Although the feedback-based model is not superior to the optimal control model regarding achievements of the objectives, the authors reported that the feedback-based model is applicable in the real world because it does not use an online model or demand predictions. However, until now, field tests of the strategy have not been conducted. Therefore, to support the practical aspects of VSL, Müller et al. (2015) proposed a micro-simulation analysis of VSL using AIMSUN. In their research, they implemented a VSL system similar to the real-world environment, such as ways of applying section-level VSL or point-level VSL, the length of the application area, and the length of the acceleration area (Figure 5). They concluded that section-VSL is preferable to point-VSL, and that the shorter application and acceleration areas decrease delay.

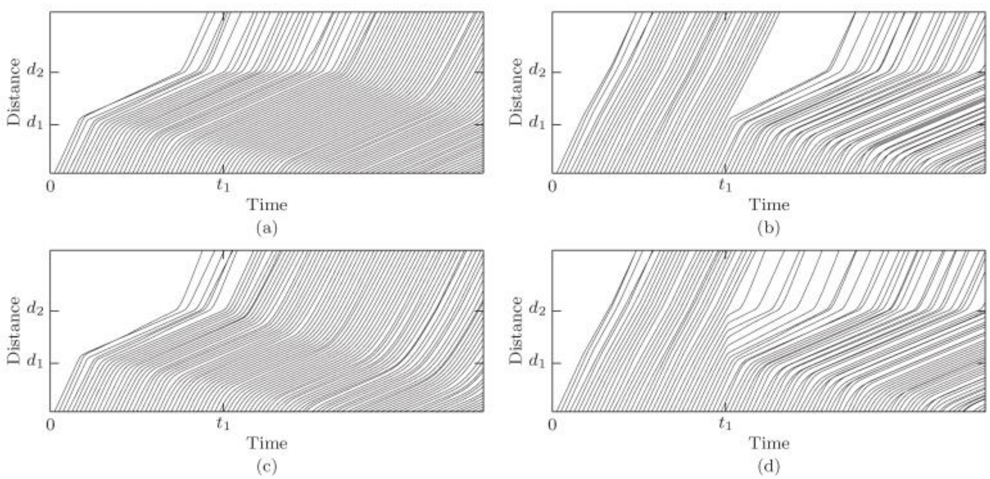

Figure 5. Graph. Time-space diagrams of point (P) and section (S) VSL applications. (a) P-VSL increase; (b) P-decrease; (c) S-VSL increase; and (d) S-VSL decrease (Müller et al. 2015)

COMBINED VARIABLE SPEED LIMIT-RAMP METERING ALGORITHM AT MERGE BOTTLENECK

In RP14-14 (Laval et al. 2019), the PI and his team propose a new VSL strategy designed to increase capacity at metered on-ramp bottlenecks and show that it can reduce travel times by 8% in the corridor.

In this strategy, the VSL system is not activated until the ramp queue spill back is detected. Two detectors for spill back detections are required. The flow process is shown in Figure 6. If traffic density at D_1 is less than critical density k_c, only ramp metering system is activated. If not, VSL1 is activated. At the same time, if traffic density at D_1 is greater than critical density k_c, VSL2 is activated. (Cho et al. 2020, Cho and Laval 2020)

$$\text{VSL1: } v = \frac{w(\alpha\mu_f - \beta\lambda_1)}{wK - (\alpha\mu_f - \beta\lambda_1)}$$
$$\text{VSL2: } v = \frac{w(\mu_f - \lambda_1)}{wK - (\mu_f - \lambda_1)}$$

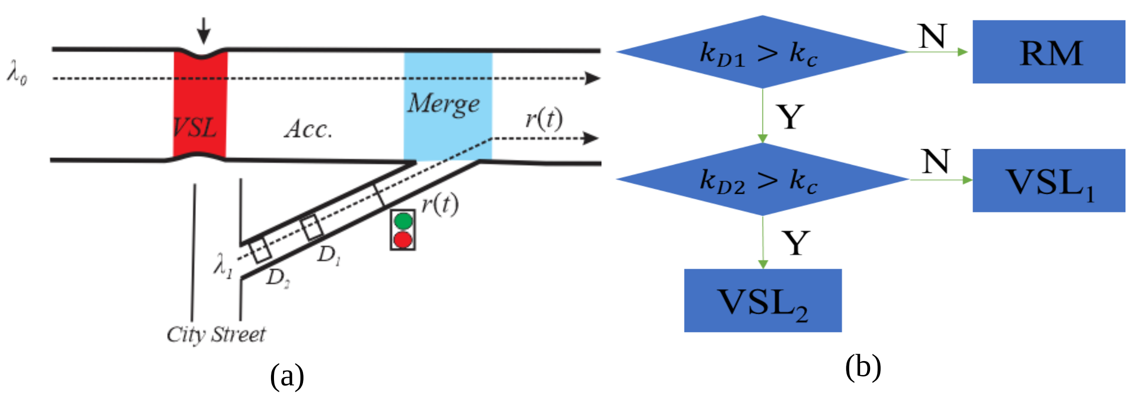

Figure 6. Illustration. (a) Scheme of combined queue-controlled RM and VSL (strategy A) (b) Queue controlled RM and VSL (strategy A) process

In VSL1, $\alpha\mu_f$ is the target freeway capacity of the VSL system, $\beta\lambda_1$ is the new metering rate during the queue warning period, λ_1 is the real-time traffic demand of the on-ramp.

A shoulder lane control only strategy is also introduced in RP14-14. This strategy is an extended version, in which the VSL system is applied only to the shoulder. The speed of VSL follows the same equation but in this study the capacity of the shoulder lane is only used to calculate the speeds.

CHAPTER 3. METHODOLOGY

STUDY CORRIDOR

The study involved the selection of two merge bottlenecks in the I-285 corridor. Based on the speed-contour map, the research team selected Memorial Drive and Chamblee Tucker Road as the study ramps (see Figure 7). This study focuses on the onset period of evening peak congestion.

GTsim

GTsim, which is built based on a kinematic wave model, is the first one of its kind proven to replicate traffic dynamics during congestion. GTsim implements the latest lane-

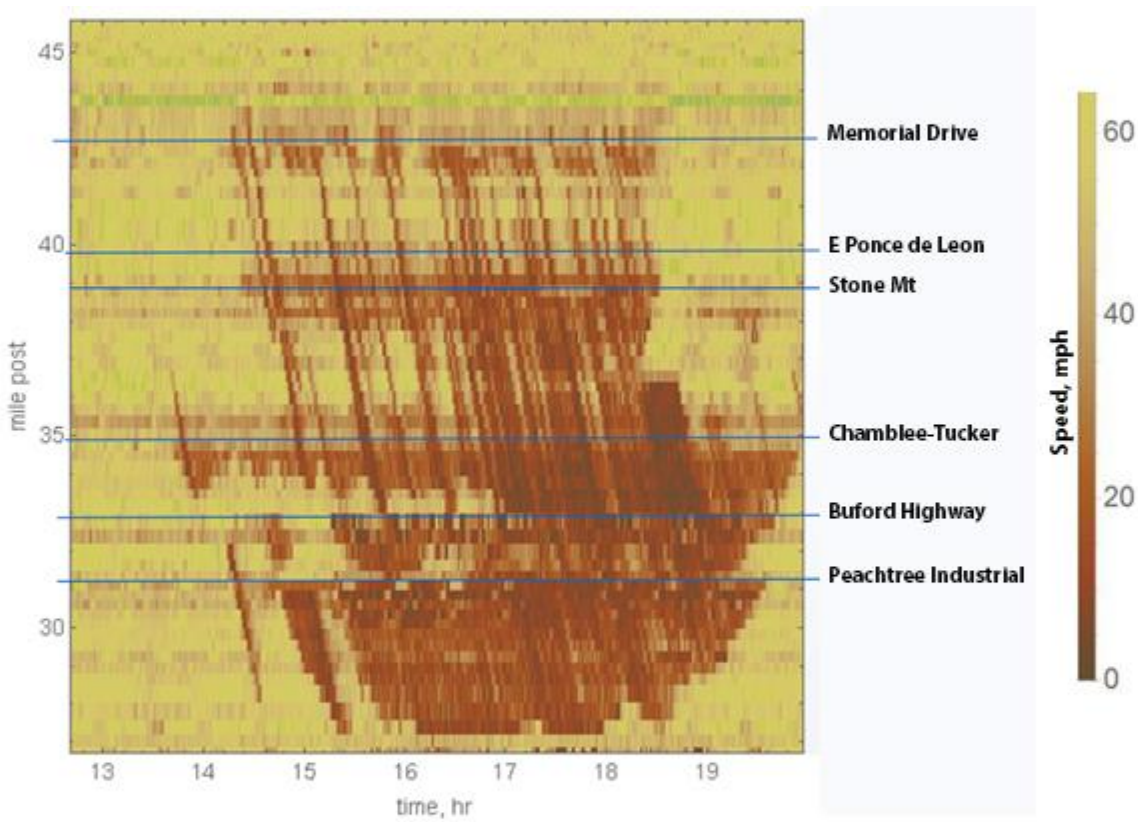

Figure 7. Graph. The speed contour map for the study corridor, where different colors indicate different vehicle speeds.

changing models, which significantly improved understanding of traffic congestion. Specific explanations on GTsim modules were introduced in the final report of the "Development of Optimal Ramp Metering Strategies" study. (Guin and Laval 2013)

TRAFFIC DATA ANALYSIS

Data

Within the study corridor, this study used GDOT NaviGAtor's Vehicle Detection System (VDS) data that collected 20-second interval volume, speed, and occupancy (hereafter referred to as the "VDS data"). This study extracted the VDS data during a one-month period (February 2019).

Traffic flow from on-ramps were inspected and five-minute volume data for 48 hours at these ramps were measured using traffic tube counts (See Figure 8).

Calibration and Validation

GTsim has several parameters that must be calibrated. (Chilukuri et al. 2014) The parameters are categorized into capacity parameters (i.e., free-flow speed, jam density, and wave speed), lane-changing parameters (i.e., longitudinal distance between a vehicle and an exit ramp), tau (i.e., time to execute a lane-changing maneuver), epsilon (i.e., relaxation speed gap), and driver behavior parameters (friction speed). These calibrated parameters are summarized in Table 1. All parameter values in Table 1 are used for the two on-ramps.

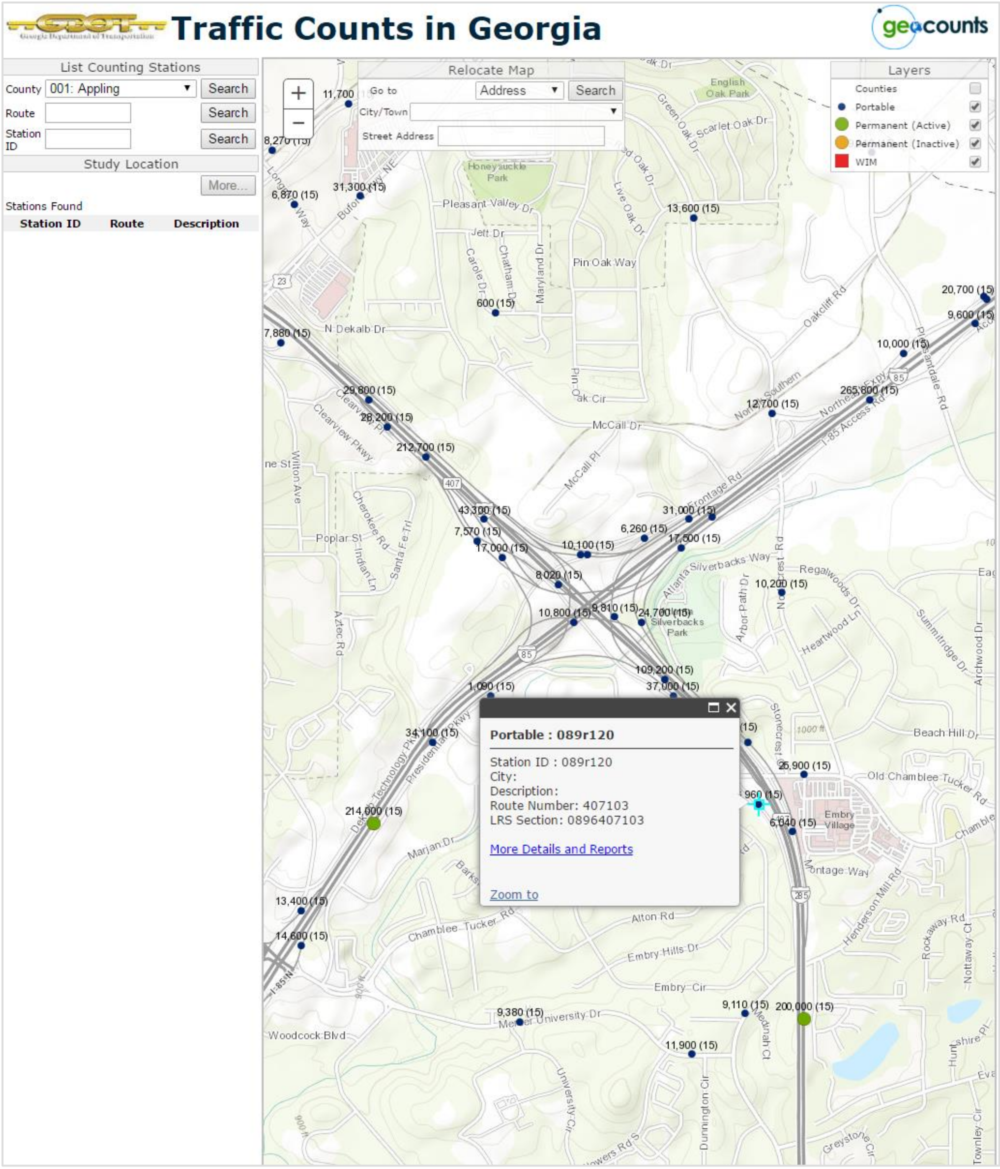

Figure 8. Screenshot. GDOT Traffic Tube Counts

The research team used NaviGAtor's VDS data (2019/02/12) to generate the optimal parameters in Table 1 by comparing the speed 0.5 km downstream of the merge between NaviGAtor's VDS data and GTsim simulation results. The research team validated the model using the VDS data from another day (2019/02/06) and the replicated average speed is within 10% accuracy.

Table 1. Calibrated Parameters

Calibrated Parameter	Parameter Value
Free-flow speed	100 *km/hr*
Jam density	150 *veh/km*
Wave speed	20 *km/hr*
Longitudinal distance between a vehicle and an exit ramp	2 (4) *km*
Tau (time to execute a lane-changing maneuver)	4 *s*
Epsilon (relaxation speed gap)	2
Friction speed	20 *km/hr*

Finding optimal control strategy

For the selected two on-ramps, the research team first finds the optimal Kr, maximum and minimum metering rate vales for the ramp metering only strategy. Then, the team studied TORBO strategy. During the optimization process, the following parameters were optimized through grid search: α, β, Kr, VSL zone length, maximum metering rate and minimum metering rate for both all lane VSL and shoulder-lane-only VSL. The optimal parameters are shown in the next chapter.

Table 2. Parameter calibration and validation

Date	**Speed in VDS data (km/h)**	**Speed in GTsim† (km/h)**
2019/02/12 (calibration)	89.126	89.139 (+0.01%)
2019/02/06 (validation)	95.019	88.810 (-6.53%)

† Numbers in parentheses indicate the percentage difference between VDS and GTsim speeds

CHAPTER 4. RESULTS

The results of the simulation-optimization for three cases (no control, the RM control only, the VSL-RM control) are summarized in Table 3 and Table 4. We found that the performance of the VSL-RM control with optimized parameters outperforms the RM control only model with its optimized parameters in terms of reducing total travel time.

Table 3. Travel time (vehicle hours) comparison of no control, the RM control only, and the VSL-RM control cases for Memorial Drive

Case	System	Freeway	Ramp
No control	297.3	264.6	32.7
RM control only†	292.3 (-1.7%)	232.4 (-12.2%)	59.9 (83.1%)
VSL-RM control†	284.3 (-4.4 %)	229.7 (-13.2%)	54.6 (66.8%)

† Numbers in parentheses indicate the percentage difference compared to the No control case

Table 4. Travel time (vehicle hours) comparison of no control, the RM control only, and the VSL-RM control cases for Chamblee Tucker Road

Case	System	Freeway	Ramp
No control	467.7	444.1	23.6
RM control only†	460.6 (-1.5%)	410.3 (-7.6%)	50.3 (113.2%)
VSL-RM control†	451.8 (-3.4 %)	397.8 (-10.4%)	51.0 (116.1%)

† Numbers in parentheses indicate the percentage difference compared to the No control case

Table 5 summarizes the optimal parameter values of the RM only system and the VSL-RM system. Only shoulder lane VSL should be activated.

Table 5. Optimal parameter values of the RM only and VSL-RM models

Location	Memorial Dr	Chamblee Tucker Rd
$\boldsymbol{K_R}$ (RM only)	75	100
Max metering rate (RM only)	1425	1425
Min metering rate (RM only)	400	700
$\boldsymbol{K_R}$ (VSL+RM)	45	96
$\boldsymbol{\alpha}$	1.24	1.13
$\boldsymbol{\beta}$	0.83	0.90
VSL Zone Length	50 m	150 m
Max metering rate (VSL+RM)	1425	1425
Min metering rate (VSL+RM)	400	700

CHAPTER 5. CONCLUSIONS

The research team performed a detailed micro-simulation and fine-tuning of the VSL control strategy TORBO at two merge bottlenecks in the I-285 corridor. By determining optimal parameter values of the combined VSL-RM systems, the research team compared the minimum total travel time of the two systems to the no control case. It was found that the optimal values derived from this case study, compared to the no-metering case scenario, reduce travel times by more than 4 %. We also found that the current GDOT VSL control strategy increases travel time by 5%, the implementation of the proposed method could lead to close to 10% travel time savings compared to the status quo. The optimal parameter values derived in this case study are temporal and location sensitive and need to be optimized for other locations and time periods.

Unfortunately, the field implementation was not possible due to technological limitations in the IT infrastructure that cannot be circumvented within the time and funding scope of this project. In particular, the VSL data from NaviGAtor cannot be interfaced in real time with the ramp-metering data from MaxView. Hopefully, these technological setbacks will be removed going forward to allow for efficient congestion management in Georgia freeways.

REFERENCES

Abdel-Aty, M., Cunningham, R. J., Gayah, V. V., and Hsia, L. (2008). "Dynamic variable speed limit strategies for real-time crash risk reduction on freeways." *Transportation Research Record* 2078 (1):108-116.

Abdel-Aty, M., Dilmore, J., and Dhindsa, A. (2006). "Evaluation of variable speed limits for real-time freeway safety improvement." *Accident analysis & prevention* 38 (2):335-345.

Bertini, R. L., Boice, S., and Bogenberger, K. (2006). "Dynamics of variable speed limit system surrounding bottleneck on german autobahn." *Transportation Research Record* 1978 (1):149-159.

Carlson, R. C., Papamichail, I., and Papageorgiou, M. (2011). "Local feedback-based mainstream traffic flow control on motorways using variable speed limits." *IEEE Transactions on Intelligent Transportation Systems* 12 (4):1261-1276.

Carlson, R. C., Papamichail, I., and Papageorgiou, M. (2014). "Integrated feedback ramp metering and mainstream traffic flow control on motorways using variable speed limits." *Transportation research part C: Emerging technologies* 46:209-221.

Carlson, R. C., Papamichail, I., Papageorgiou, M., and Messmer, A. (2010a). "Optimal mainstream traffic flow control of large-scale motorway networks." *Transportation Research Part C: Emerging Technologies* 18 (2):193-212.

Carlson, R. C., Papamichail, I., Papageorgiou, M., and Messmer, A. (2010b). "Optimal motorway traffic flow control involving variable speed limits and ramp metering." *Transportation Science* 44 (2):238-253.

Chen, D., and Ahn, S. (2015). "Variable speed limit control for severe non-recurrent freeway bottlenecks." *Transportation Research Part C: Emerging Technologies* 51:210-230.

Chilukuri, B. R. (2015). "Optimal Ramp Metering of Freeway Corridors." Georgia Institute of Technology.

Chilukuri, B. R., Laval, J. A., and Chen, D. (2013). Some traffic features during on-ramp queue flush.

Chilukuri, B. R., Laval, J. A., and Guin, A. (2014). "Microsimulation-based framework for freeway travel time forecasting." *Transportation Research Record* 2470 (1):34-45.

Cho, H. W., Chilukuri, B. R., Laval, J. A., Guin, A., Suh, W., and Ko, J. (2020). "Genetic algorithm-based simulation optimization of the ALINEA ramp metering system: a case study in Atlanta." *Transportation Planning and Technology*:1-13.

Cho, H. W., and Laval, J. A. (2020). "Combined Ramp-Metering and Variable Speed Limit System for Capacity Drop Control at Merge Bottlenecks." *Journal of Transportation Engineering, Part A: Systems* 146 (6):04020033.

Guin, A., and Laval, J. A. (2013). Development of Optimal Ramp Metering Strategies Final Report (GDOT Research Project TO 02-98; RSCH PROJ 11-18 Georgia Tech Project No. 2006S18).

Han, Y., Chen, D., and Ahn, S. (2017). "Variable speed limit control at fixed freeway bottlenecks using connected vehicles." *Transportation Research Part B: Methodological* 98:113-134.

Hegyi, A., De Schutter, B., and Hellendoorn, J. (2005). "Optimal coordination of variable speed limits to suppress shock waves." *IEEE Transactions on intelligent transportation systems* 6 (1):102-112.

Hegyi, A., Hoogendoorn, S. P., Schreuder, M., Stoelhorst, H., and Viti, F. (2008). "SPECIALIST: A dynamic speed limit control algorithm based on shock wave theory." 11th international IEEE conference on intelligent transportation systems.

Khondaker, B., and Kattan, L. (2015). "Variable speed limit: A microscopic analysis in a connected vehicle environment." *Transportation Research Part C: Emerging Technologies* 58:146-159.

Laval, J. A., Guin, A., Chilukuri, B. R., and Cho, H. W. (2019). Travel-time Optimization on I-285 with Improved Variable Speed Limit Algorithms and Coordination with Ramp Metering Operations. Georgia Institute of Technology. School of Civil and Environmental Engineering.

Lee, C., Hellinga, B., and Saccomanno, F. (2006). "Evaluation of variable speed limits to improve traffic safety." *Transportation research part C: emerging technologies* 14 (3):213-228.

Müller, E. R., Carlson, R. C., Kraus, W., and Papageorgiou, M. (2015). "Microsimulation analysis of practical aspects of traffic control with variable speed limits." *IEEE Transactions on Intelligent Transportation Systems* 16 (1):512-523.

Papageorgiou, M., Hadj-Salem, H., and Middelham, F. (1997). "ALINEA local ramp metering: Summary of field results." *Transportation research record* 1603 (1):90-98.

Papageorgiou, M., Kosmatopoulos, E., and Papamichail, I. (2008). "Effects of variable speed limits on motorway traffic flow." *Transportation Research Record* 2047 (1):37-48.

Papageorgiou, M., and Kotsialos, A. (2002). "Freeway ramp metering: An overview." *IEEE transactions on intelligent transportation systems* 3 (4):271-281.

Smulders, S. (1990). "Control of freeway traffic flow by variable speed signs." *Transportation Research Part B: Methodological* 24 (2):111-132.